Multiple-Charge-State-Beam Steering in the RIA Driver Linac

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Abstract

The RIA driver linac is required to accelerate beams of any ions, including uranium, and it has been designed to accelerate multiple-charge states as an efficient means to increase the available beam current. Acceleration of multi-charge states of the heaviest ions requires that intercavity and intercryostat drift spaces be kept to a minimum to reduce the amplitude of longitudinal oscillations. The complexity and compactness of the driver linac impose strict conditions on the design of a corrective steering procedure. A correction algorithm has been designed with the requirements that it preserve the beam quality by minimizing the effective emittance growth and obey the constraints imposed by the real-estate limitations. The algorithm takes into consideration the coupling induced by the focusing solenoids and minimizes the amplitude of coherent oscillations of the multi-charge beam in the transverse phase space. The algorithm is based on the determination of response functions by the focusing sections to induced beam-centroid oscillations. A goal function that includes measured and induced trajectory deflections is then minimized by sweeping the corrector strength parameter space. The procedure is applied to simulations of transverse misplacements of solenoids and SRF cavities, in the low- and medium-β driver sections, where steering is most demanding. Several correcting schemes are examined to determine the most effective steering requirements, and the displacement error tolerance is determined. In this paper, we report the results of simulations using the correction algorithm to investigate and correct alignment errors in the low-and medium-energy sections of the driver. Future developments include testing the algorithm efficiency under real-machine conditions at the superconducting linac of the heavy-ion ATLAS facility.

INTRODUCTION

The RIA driver will have a high degree of complexity, as demanded by the large number of components, several different types of independently phased SC resonators, and the number of different accelerated beams. RIA is designed to produce beams of any ions, including uranium, at energies of 400 MeV/nucleon and beam power of 400 kW. This amount of power requires an uranium beam current of about 4 pμA, which can be achieved by simultaneous acceleration of multiple charge states [1]. Acceleration of multiple charge states, in turn, affects the beam dynamics. The different charge states have slightly different betatron periods that can become uncorrelated as the beam advances through the driver and the effective total emittance increases. In particular, the effective emittance growth is strongly affected by misalignments of the focusing elements. Inter-cryostat spaces and spaces between resonators in the low- and medium-beta sections of the driver adversely affect the longitudinal beam dynamics, and are therefore kept to a minimum. This places restrictions on the choice of steering and diagnostics configuration. Acceleration of different ions require different accelerator parameters for tuning, and a rapid tuning procedure.

The machine complexity, the acceleration of multiple-charge-states, the tight real estate, and the need for frequent and fast machine retuning place strong requirements on the steering algorithm.

METHOD AND CORRECTION ALGORITHM

The multi-charge-state emittance is much smaller than the accelerator acceptance, but misalignments of the focusing components, passage through two strippers, and non-linear elements in the transport lattice can lead to excessive emittance growth. An effective steering algorithm should control emittance growth and reduce large trajectory excursions, to avoid losses. One important additional requirement is that it be incorporated into the tracking simulation code TRACK [2] to facilitate studies of beam losses along the accelerator. Finally, the algorithm should be implement-able in a real machine environment.

In most linacs, where it is possible to establish a one-to-one correspondence between correctors and beam position monitors (BPMs), one attempts to zero out the beam position at a BPM by varying the strength of an upstream dipole corrector. With this procedure, the trajectory at each BPM can be minimized within precision and corrector-strength limitations. The lower-energy sections of the RIA driver allow limited space for diagnostics. The drifts between cryostats will contain only vacuum valves and a (BPM). Steering will be provided by coils combined with the SC focusing solenoids to eliminate additional drift spaces [3], and a many-to-one algorithm is required. In addition, the correction algorithm should correct both position and angle. An essential requirement is that the algorithm addresses the coupling of the horizontal and vertical motions induced by the focusing SC solenoids.

Our algorithm is based on the determination of the beam response functions to known induced excitations to the beam trajectory, and on the minimization of a goal function that depends on those response functions. We assume that the beam centroid can be mapped by functions relating the initial phase-space coordinates at a point s_0 to its coordinates at a point s along the accelerator. These *transfer functions* describe the lattice responses at s to the beam conditions at s_0. Given N misaligned elements, we need in general 2N+4 measurements of the beam position and angle at the BPMs to determine the misalignments and initial conditions. In the RIA case, because of the lattice constraints, the BPMs are located outside the cryostats, and there are two or more solenoids per cryostat. Therefore, the equations describing the beam motion cannot be solved exactly and we resort to a "least-square" solution to the trajectory equations. To correct the trajectory we introduce additional perturbations by activating correctors placed along the accelerator. The lattice response functions are calculated by inducing deflections of a known magnitude and measuring the changes in the beam coordinates at the BPMs. Our algorithm optimizes a goal function Φ to reduce the measured trajectory deviations to a minimum. Φ depends on the measured beam coordinates, on the transfer functions, and on the unknown corrector strengths. The set of transfer functions contains those elements that describe the coupling of the horizontal and transverse motions. We seek corrector strengths that minimize the function Φ, subject to the constraints imposed by the corrector strength limits. The algorithm has been implemented in the TRACK code. In this paper, we report the results of simulations using the correction algorithm to investigate and correct alignment errors in the low-and medium-energy sections of the driver.

THE LOW-ENERGY LINAC SECTION

The low-energy section precedes the first stripper and can accelerate uranium atoms of charge 28 and 29 from 190 keV/u to 12 MeV/u. There are 85 SC cavities distributed in ten cryostat modules. The geometrical beta ranges from 0.024 to 0.15. Focusing is provided by SC solenoids, and the transverse focusing length varies from 54.9 cm to 177.3 cm, with field strengths varying from 7 to ~10Tesla.

Misalignments of the transverse position of the focusing elements affect the beam dynamics most severely [1]. Since low-velocity particles are defocused by the SRF cavities, cavity misalignments were also included in the analysis. We simulated the effects of solenoid and cavity misalignments on the uranium beam dynamics, with errors following a random uniform distribution of interval $\pm\sqrt{3}\delta$, where δ varied from 0.17 mm to 0.57 mm. In what follows we present the results from corrections of 1-mm uniform (0.57-mm rms) random misalignments in solenoids and cavities. In the simulations, correctors are represented by thin (delta-function) elements. In the machine, correctors will be realized by dipole coils superimposed on solenoids. Of the many corrector distribution schemes investigated, two were the most effective. In one scheme, correctors were superimposed on every two solenoids, in a total of 23 correctors. In the second scheme, a single corrector was placed on the last focusing element of each cryostat, totaling ten correctors. Both schemes had one corrector upstream of the first cryostat and ten monitors, each monitor placed in the space between the cryostats.

Figure 1 compares the histograms of the horizontal emittance-growth factor, in percent, for a 200-seed simulation of 1-mm misalignments, corrected by the two schemes. Here, the emittance-growth factor is the percentage change in the normalized emittance value at the exit from that at the beginning of the section. As shown, the most probable effective percentage growth is 4% for correction-scheme 1, and 6%, for scheme 2. This is not surprising, since more correction elements should result in lower effective emittance growth. Of interest is the spread in both distributions, markedly the spread resulting from the scheme-2 correction: the distribution is more spread than the scheme-1 distribution by a factor of four. The outliers around 20% could lead to halo formation.

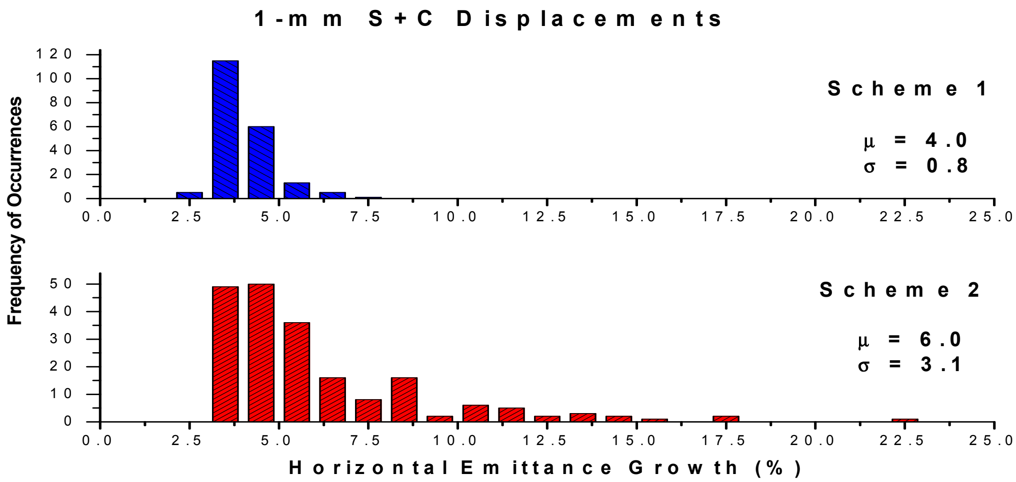

Figure 1: Emittance growth factor for 1-mm solenoid and cavity misalignments in the low-β section, histogrammed over 200 seeds. Scheme 1 indicates correction by 23 correctors, and 10-monitors, scheme 2, correction by ten correctors and ten monitors.

One of the algorithm requirements was the correction of position and slope, by minimizing the centroid coordinates at the monitors. As can be seen in Figure 2, obtained with scheme-2 correction, the centroid positions are reduced by an average factor of four in the first monitors, and by a factor of ten or higher in most of the upstream moniotors.

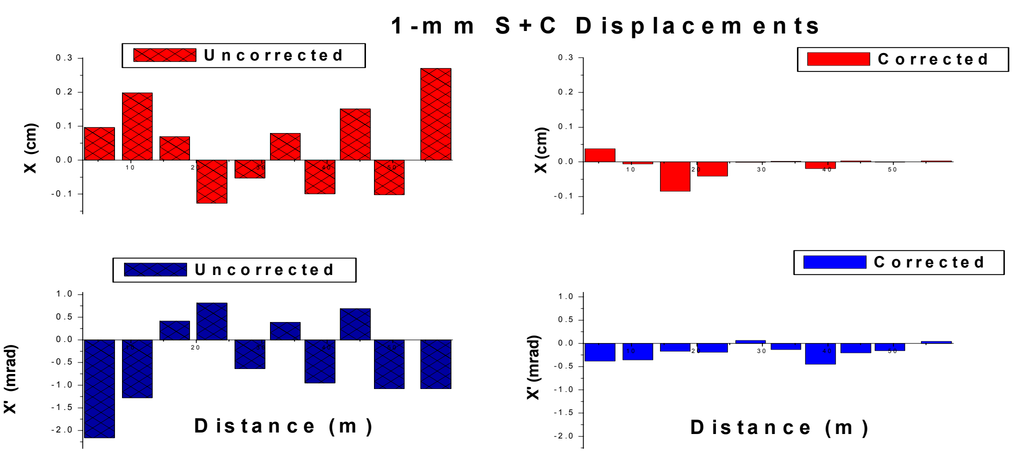

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Figure 2: Beam-centroid coordinates at the monitors are shown before (left side) and after (right side) correction by the ten-corrector, ten-monitor scheme. The upper plots show the centroid positions, and the lower plots, the centroid slopes.

The slope correction is also quite effective, with a factor of 10 or more reductions for most seeds. The maximum integrated corrector strength for all seeds and in both schemes is less than 0.6 T.cm. With a estimated strength provided by a prototype solenoid-mounted dipole coil of 1 kGauss [3], and assuming a 20-cm-length corrector, the maximum corrector strength required by either scheme is well within the estimated limit.

THE MEDIUM-ENERGY SECTION

In the medium-energy section of the driver, the energy is raised from 12 to 85 MeV/u. This section follows the first stripper in the driver, and the uranium beam contains five charged-states, ranging from 69 to 73, after passage through the stripper. The beam transverse and longitudinal emittances are increased due to energy straggling and scattering in the striper. The length of the focusing period increases from173 cm to 259 cm, and the focusing solenoid field increases from 6 to 10.4 Tesla. The solenoid effective length is 30 cm, and there are three solenoids per focusing period at the beginning of the section, followed by two solenoids per focusing period.

The correction results are from simulations performed over 200 seeds with solenoids and SRF cavities randomly misaligned by 0.5-mm. Here, the correctors were placed at the last solenoid in the cryostat. In Figure 3 we show the normalized emittance growth for the horizontal and vertical planes.

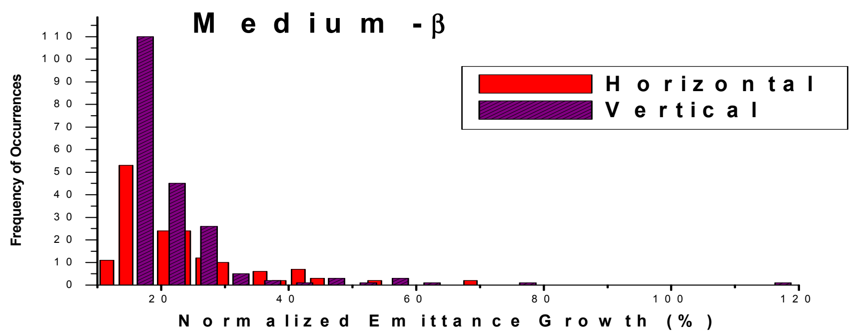

Figure 3: Normalized emittance growth for the horizontal and vertical planes. Shown are simulations over 200 seeds with 0.5-mm misalignments in solenoids and cavities, after correction.

CONCLUSIONS AND FUTURE RESEARCH AND DEVELOPMENT

The algorithm developed fulfills the requirements of integration into the existing code TRACK, and can thus be used to characterize tolerances to errors and losses. It corrects both the beam-centroid position and angle, and accounts for solenoid-induced coupling.

We will implement realistic dipole coils as correcting elements in the code. Preliminary tests have indicated that no non-linear terms are introduced by the coils. A second and essential R&D item is the experimental verification of the algorithm effectiveness, and experimental tests in the superconducting ATLAS accelerator are planned.

5 REFERENCES

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